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Reinjection of greenhouse gases into geothermal reservoirs

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ABSTRACT

This work addresses the feasibility of reinjecting H_2S and CO_2, captured and dissolved in effluents from the geothermal field, back into the geothermal reservoir. A series of numerical modelling scenarios was used to assess the effect of NCG (non-condensable gases) reinjection on energy recovery, understand permanent trapping, and forecast potential NCG breakthrough into production wells.

Although the gas species from geothermal systems typically have moderate solubility in water, formation of gas phases at lower pressures and/or the shallow subsurface requires careful consideration of the injection rate and composition of NCG. Possible fluid paths and distribution of gas components were investigated to estimate the NCG storage capability of a reservoir, and evaluate the potential risk of the reinjected NCG growing into fingers that may lead to an early breakthrough or potential leakage to the ground surface.

Modified versions of benchmark geothermal reinjection models were constructed with initial conditions of a liquid-dominated geothermal system. The results obtained show that the effects of injection depend on the reinjection and production wells arrangement and the recharge conditions. The risk of leakage to the surface is very limited since the injected NCG remain in the liquid phase.

1. Introduction

Geothermal is considered to be a clean, renewable and baseload energy source. However geothermal power production may result in some greenhouse gas emissions. Sustainable development of these resources requires methods and tools to control their environmental impacts. Reinjection is an important part of geothermal resource management, in particular, an essential part of sustainable and environmentally friendly geothermal fluid utilization. Returning some, or all, of the produced fluids back into the geothermal system helps with reservoir recharge, pressure support, and can be used to manage subsidence (ContactEnergy, 2010; Han et al., 2011). However, reinjection of geothermal brine can also cause problems, e.g., premature thermal breakthrough, groundwater contamination, and leakage of reinjected fluid to the surface. Therefore, careful reinjection strategies need to be in place to provide appropriate steam field management (Kaya et al., 2011a; Rivera Diaz et al., 2016).

Geothermal fluid contains variable quantities of NCG, consisting primarily of CO_2, H_2S, and trace quantities of some other gases (e.g. NH_3, H_2, N_2 and CH_4). These greenhouse gases originally stem from degassing magma, and, more rarely, from decomposition of organic sediments and metamorphic decarbonisation (Ármannsson et al., 2005). Depending on the geothermal fluid source, the fraction of NCG can vary from less than 0.2% to greater than 25% by weight of the geothermal fluid (Özcan and Gökçen, 2010). CO_2 is the most dominant gas, accounting for ~90% of the total NCG by volume (Bertani and Thain, 2002), while H_2S constitutes ~2% to 3%, and the other gasses constitute the remaining volume. The presence of NCG, in particular CO_2 and H_2S, in geothermal fluids often presents a challenge as these are associated with corrosion, calcite deposition, reduced power plant efficiency, and health, safety, and environmental risks (DiPippo, 2012).

The global average of CO_2 emission values from geothermal power production was 122 gCO_2/kWh in 2001, based on a survey accounting for more than 50% of the total installed geothermal capacity worldwide. However, as the geothermal sector has expanded, a wider range of geothermal resources have been brought into exploitation, including geothermal systems with relatively high NCG concentrations in the reservoir fluid. Recent data from a number of sites in Turkey (power plants located in the Menderes and Gediz Grabens) and Italy (Mt. Amiata) show that GHG emissions from geothermal power plants can be higher than 500 g/kWh and in some cases higher than emissions from coal fired power plants (ESMAP, 2016; Layman, 2017; Fridriksson et al., 2017). Although its utilization is associated with NCG emissions, geothermal energy is a relatively clean energy source. The overall CO_2 saving from geothermal electricity production worldwide can be around 1000 million tons per year (Bertani, 2016). H_2S also can be found at higher concentrations and is often a subject for local environmental concern because of its odour and toxicity. As an example,

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in 2011, the 213 MWe Hellisheidi power plant in Iceland emitted 13000 tons H_2S/year (6.96 g/kWh) to the atmosphere (Bayer et al., 2016). Note that the NCG are commonly rejected to the atmosphere in geothermal steam plants. However, not all geothermal binary power plants reject NCG if 100% reinjection back into the reservoir is implemented.

Reinjecting NCG into geothermal reservoirs to reduce the emissions of greenhouse gases and enable low-carbon electricity generation from power plants is receiving increasing interest from the geothermal industry. The NCG could be injected in the form of gas dissolved in water or as supercritical fluid. A brine-NCG mixture enhances residual trapping, prevents geomechanical damage due to overpressure, and avoids risk of gas leakage from the reservoir. There is also lower risk of salt precipitation due to formation dry-out (Ott et al., 2015; Pruess and Müller, 2009). NCG reinjection can be beneficial for steam production because the presence of CO_2 in reservoir fluid lowers the flash-point pressure of the fluid mixture, promotes boiling, and increases the enthalpy of the produced fluid. Boiling induces the formation of a gas phase in the reservoir and helps maintain a higher total reservoir pressure. However, the breakthrough of CO_2 and cold water can reduce the lifetime of geothermal production wells. To understand the migration and impact of injected gases in a reservoir and forecast effects on reservoir pressure, production enthalpy, and the potential breakthrough of reinjection fluid to the production wells, numerical reservoir simulation studies are required.

NCG reinjection has been applied to geothermal reservoirs in a few fields including: Hijiori (Yanagisawa, 2010); Ogachi (Kaieda et al., 2009); Hellisheidi (Alfredsson and Gislason, 2009); Coso (Nagl, 2010; Sanopoulos and Karabelas, 1997) and Puna (Richard, 1990). At Hijiori, Ogachi, and Hellisheidi, CO_2 was dissolved in water at very low concentrations (0.01–3% by weight) prior to injection. The Coso geothermal field has been accepting dissolved NCG in the reinjection water but operations later switched to an H_2S removal system due to reduced reservoir performance (Nagl, 2010). An initial pilot test and subsequent large scale experiment in Hellisheidi power plant demonstrated solubility storage of NCG, as well as mineral trapping of more than 80% of the injected dissolved NCG in basaltic formations (Aradóttir et al., 2015; Gunnarsson et al., 2013; Ingimundarson et al., 2015). A field CO_2 injection experiment was conducted in Ogachi hot dry rock geothermal site (Kaieda et al., 2009) by injecting river water and dry ice in a granitic rock reservoir to study the feasibility for carbon storage. Their results indicate that the CO_2 remained in the reservoir either through mineral precipitation or dissolution in the reservoir fluid.

The injection of dissolved NCG will promote water-rock interactions when water flows through a permeable reservoir matrix. A growing number of experiments and numerical simulation studies have been conducted to explore the prevalent reaction mechanisms and in rock-CO_2-H_2S-water environments (Aradóttir et al., 2015; Passarella et al., 2015; Sonney and Mountain, 2013). These chemical reactions result in different precipitation and/or dissolution of minerals at equilibrium or kinetic and rock alteration assemblages that can change the porosity and permeability of the original rock matrix. Predictive reactive transport simulations indicate mineral capture of H_2S and CO_2 is a viable option for reducing NCG emissions as they result in fast mineralization of the injected gases (Saldaña et al., 2016; Aradóttir et al., 2015; Xiao et al., 2009).

The effects of adsorption on reservoir performance have been discussed for geothermal reservoirs (Economides and Miller, 1985; Hornbrook, 1994; Pruess and O'Sullivan, 1992; Shang et al., 1995) and for methane storage systems and coal-bed methane reservoirs (Anbarci and Ertekin, 1991; Matranga et al., 1992; Zarrouk, 2008). The presence of an adsorbed phase can play a major role in the storage and pressure depletion characteristics of a reservoir. The relationship between adsorbed mass and pressure can be represented through the adsorption isotherms. An adsorption isotherm describes the equilibrium relationship between the partial pressure of the adsorbate and the amount adsorbed at constant temperature. The shape of the isotherm may vary substantially depending upon the nature of the adsorbent (both chemical composition and physical structure) and the adsorbate. A straightforward method of determining the effects of this adsorbed mass on pressure would allow simple determination of adsorption effects.

This work investigates the possible impacts of reinjection of a water-CO_2-H_2S mixture in two-phase liquid-dominated geothermal reservoirs using modified versions of an idealized numerical model developed by Kaya and O'Sullivan (2006) as a representative case study. Various reinjection scenarios were tested to investigate the effect of water-only and water-NCG mixture in a geothermal reservoir, in particular, on the longevity of the resource with regard to steam production. Possible flow pathways for injected fluid were investigated in order to identify potential breakthrough and leakage risks.

Simulation of aqueous phase chemical equilibria and water-rock reactions driven by the injection of water and gas mixtures is not considered in this study. However, in this work the effect of chemical reactions between NCG and rock minerals that could potentially contribute to mineral trapping of NCG was considered by including adsorption behaviour of CO_2-H_2S-water mixtures. Adsorption determines the maximum gas holding capacity (a measure of the amount of gas that can be held by a unit volume of reservoir rock at a particular pressure and temperature), and was represented through Langmuir adsorption isotherms to understand the NCG storage capability of a reservoir. The breakthrough of NCG was also monitored, since higher gas production can result in lower energy recovery due to the higher parasitic load needed to remove these gases from the power plant condenser. Numerical experiments were carried out for various reservoir and production conditions, as well as boundary effects such as closed side boundary, hot side recharge, and warm side recharge. A larger-scale geothermal field was also considered for these experiments.

When the NCG are co-injected with water, they mainly dissolve in the aqueous phase, but the pressure drop during production induces formation of a supercritical gas-like phase that has a much lower viscosity and density than the dissolved NCG. This may cause a rise of gas components to the surface with the effect of buoyancy forces. The geothermal equation of state currently used in the TOUGH2 packages (e.g EOS2, EOS4, EWASG) make it possible to simulate flow of water and a separate gas component, such as air-water for EOS4, CO_2-water for EOS2, and a choice of one type of NCG (air, CO_2, CH_4, H_2 or N_2) for EWASG in order to represent multicomponent systems and their temperature- and pressure-dependent gas dissolution. However, implementing one gas component of NCG is not adequate for monitoring the distribution of NCG injected into a reservoir, especially in the shallow vadose zones that mainly contain air. Therefore, in this study, we employ a modified version of the ECBM-TOUGH2 equation of state (Zarrouk and Moore, 2009), which was originally developed for modelling enhanced coalbed methane (ECBM). ECBM-TOUGH2 incorporates gas properties from the equations of EWASG (Battistelli et al., 1997) and EOS11 (Zarrouk, 2008) and can handle non-isothermal multiphase flows of water and CO_2, N_2, H_2S and CH_4 gas compositions. Representation of NCG trapping is also possible using adsorption parameters. The multi component version of the Langmuir adsorption isotherms was applied following Zarrouk and Moore (2009).

ECBM-TOUGH2 has been used on several test problems and the model results have been compared with results from existing commercial packages (Moore and Zarrouk, 2011; Zarrouk, 2008; Zarrouk and Moore, 2009). The models have been used successfully in the assessment of the potential of several CBM fields in New Zealand and overseas. For visualisation and post-processing, TIM (Yeh and Croucher, 2013) and PyTOUGH software (Wellmann et al., 2012) were used respectively.

2. Modelling of water-NCG mixture reinjection

The purposes of this study are to investigate the effect of NCG-water